Scattering from Rock and Rock Outcrops

Derek R. Olson
The Pennsylvania State University
Applied Research Laboratory, P.O. Box 30
State College, PA 16804-0030
phone: (814) 863-9895 fax: (814) 863-8783 email: dro131@psu.edu

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LONG-TERM GOALS

In terms of target detection and classification, scattering from exposed rock on the seafloor, (i.e., individual rocks and rock outcrops) presents some of the most difficult challenges for modern MCM and ASW sonar systems in shallow water. Work on characterizing, modeling and simulating mean levels, and other statistical measures of acoustic scattering from rocks and rock outcrops is therefore critical. Unfortunately (and curiously) information on scattering from underwater rock and outcrops is almost non-existent. Scattering from rock outcrops is not simple enough to be encompassed by a single scattering strength curve, but has a variety of expressions depending on the exact geomorphology of the rock. Smoothed surfaces may actually scatter less than surrounding sediment; curvature may dramatically affect scattering and rough areas as seen on the rock outcrop in *Figure 1*, display high variability which could pose difficulty for target detection and classification systems.

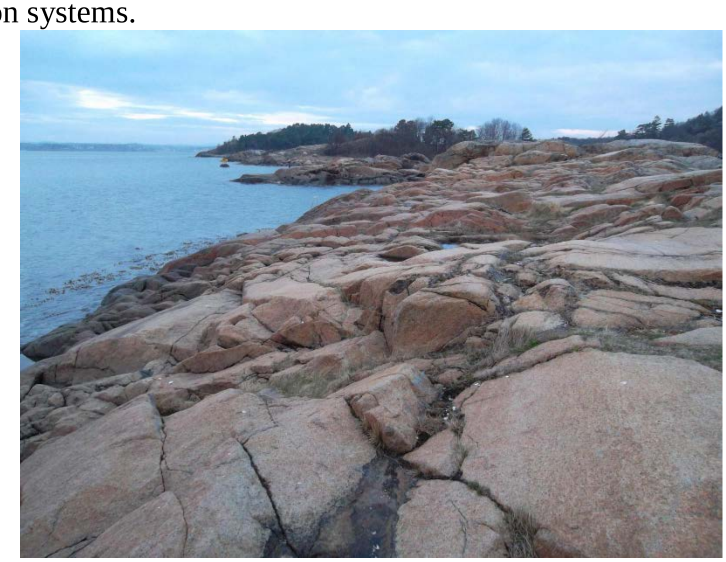

Figure 1 Photo of rock outcrop in the Oslofjord near Larvik, Norway. The outcrop is similar to underwater outcrops from which acoustic scattering was collected.

The primary long-term goal of this research project is to increase understanding and modeling capabilities for high-frequency acoustic scattering from rock and rock outcrops. In addition to an increase in basic understanding of the characteristics of scattering from rock, any resulting advances in modeling would be useful for improving simulation capabilities and for improving detection and classification tools. Inverse models based on forward models would be essential for using sonar systems for remote sensing of seafloor properties. An understanding of spatial coherence functions for isotropic and anisotropic rough seafloor surfaces could allow a method for separating natural 'target'-like objects such as rough rock from man-made targets.

OBJECTIVES

Our objectives for the proposed study of scattering from rocky seafloors and rock outcrops are intended to address many of the open questions which exist for scattering from these types of surfaces and include increasing our basic understanding of:

1) geoacoustic characteristics of rock relevant to scattering,
2) scattering strength versus grazing angle, and
3) coherence in angle or frequency of scattering from rock.

These goals will be achieved through examination of existing literature, analysis of field data or lab measurements and by the use of extended approximate or numerical scattering models.

APPROACH

The proposed work will involve:

(1) Examining the literature on the morphological and geo-acoustic characteristics of various types of rock (e.g. roughness, facet size distribution, bulk properties),

(2) Acquiring and analyzing acoustic and environmental data collected during field tests in areas of known rock outcrops, and

(3) Modeling acoustic scattering by adapting existing approximate models or using numerical scattering techniques such as finite element or boundary element models.

Using broadband wide-aspect acoustic data (available, for example, from synthetic aperture sonar systems) we will characterize scattering from rock in terms of both mean levels and other statistical measures such as angular or frequency coherence and probability of false alarm (PFA). Data taken on different morphological features of rock outcrops (i.e., surfaces that are smooth, rough, curved, faceted, etc.) will be obtained and analyzed to determine the relative influence of these features on scattering characteristics such as the shape of the scattering strength versus grazing angle curves or the transition to a

Lambertian shape. Environmental data consisting of high-resolution sonar measurements (such as from interferometric synthetic aperture sonar systems) taken in the experimental areas will be used as ground truth in data/model comparisons. If environmental data do not exist, we will attempt to collect it as part of this project. Data-model comparisons will yield insight into controlling factors, identify gaps in our knowledge base and highlight deficiencies in our current scattering models. Suggestions can also be made for future studies based on knowledge gained in the proposed study.

The groundwork for this study has already been laid via a variety of ongoing projects and collaborations by the PI. Through a joint ARL-PSU research project with the Norwegian Defence Research Establishment (FFI, POC Roy Hansen) and an ONR Code 33 project which ended in FY12, we took part in an at-sea experiment in the Oslo Fjord where we acquired 100 kHz SAS data from FFI's HUGIN HISAS system on rocky objects over a wide range of sizes (from less than 1 m up to several 10's of m). The HISAS yields high-resolution interferometric bathymetry (~15 cm resolution) which can be used for estimating curvature and the larger-scale slope field. As part of an ongoing MCM Joint Research Program with the NATO Centre for Maritime Research and Experimentation, we have obtained MUSCLE SAS data (300 kHz) on individual rocks and rock outcrops. To aid in the study of angular and temporal coherence we have also obtained SAS data from NURC's 'calibrated' rock with a digitized 3D shape. We have also initiated joint research with NRL-DC (R. Gauss) to pass our characterization work on to them for use in lab and numerical scattering studies.

WORK COMPLETED

Over the course of FY15, work was performed by the PI on measuring and modeling scattering from rocky outcrops described in the first two components listed in the technical approach described above. As virtually no information exists on scattering from rock outcrops, we have worked on obtaining relevant physical characteristics of rock outcrops, such as the geoacoustic properties, roughness, and morphology for use in models of acoustic scattering from rock. This year the methods developed in previous years to estimate scattering strength from SAS data were applied to a wider set of data and reported in [1].

The historical literature was examined to determine the mineral composition of the bedrock in the area. These data [2] were used to estimate the compressional wave speed, shear wave speed, and density of rock outcrops based on Hashin-Shtrikman-Walpole bounds [3]. These measurements in conjunction with effective medium theory resulted in estimates of 6393 m/s for the compressional wave speed, 3276 m/s for the shear wave speed, and 2708 kg/m^3 for the bulk density. To provide estimates of interface roughness, an experiment was performed in May 2013 using stereo photogrammetry. Both of these types of environmental ground truth were used to compute approximate scattering models that are compared with measured data. Analysis of these data was refined in 2015 and reported in [1].

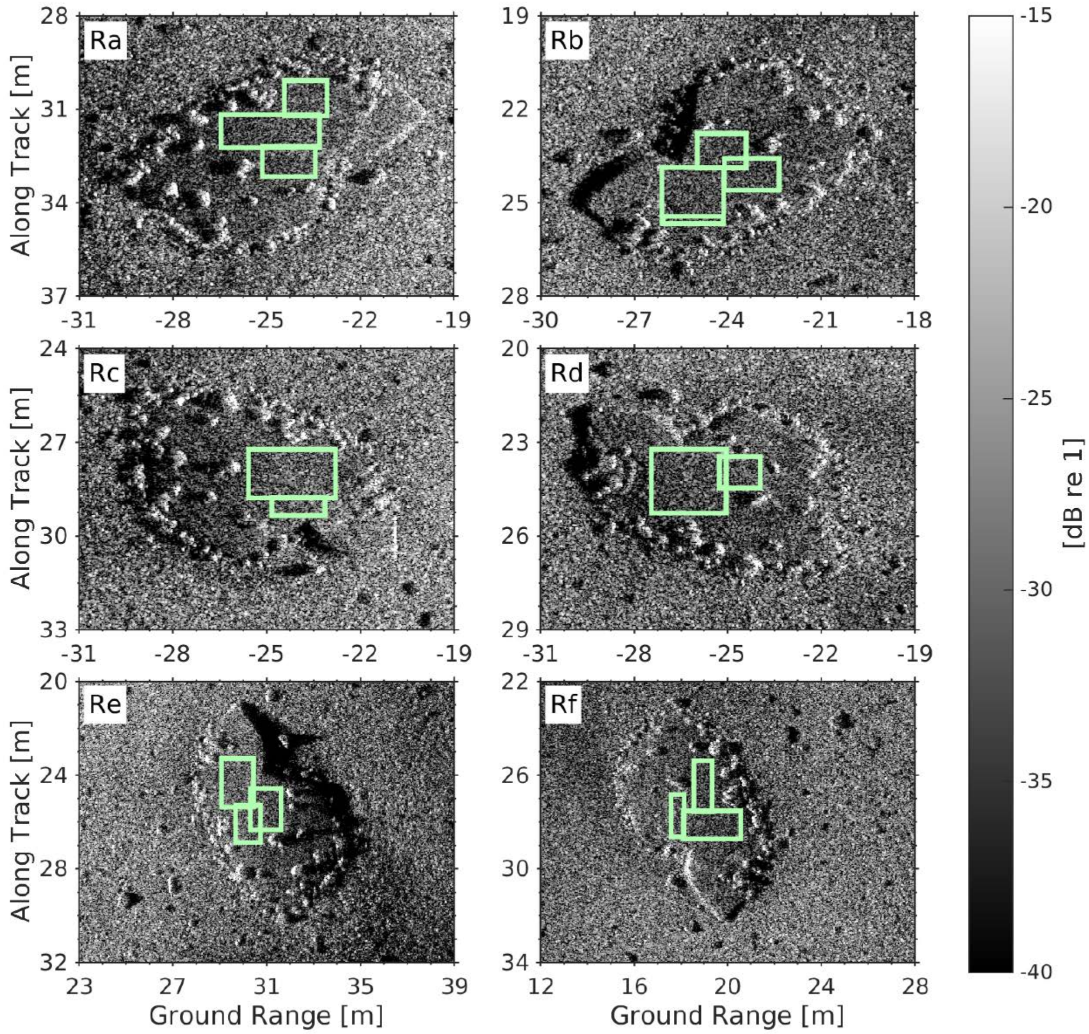

Figure 2 SAS images of a flat, glacially abraded rock from various aspects. Image value expresses the unaveraged scattering cross section in dB, and the green boxes denote pixels that are used to estimate the scattering cross section.

The sonar data analyzed was collected in April, 2011 during a joint field experiment that took place near Larvik, Norway, as part of a collaborative work with the Norwegian Defence Research Establishment (FFI). The SAS system operated at a center frequency of 100 kHz, has a bandwidth of 30 kHz and was operated from the HUGIN Autonomous Underwater Vehicle (AUV).

SAS images of a smooth, flat rock outcrop can be seen in *Figure 2* and is denoted R, and SAS images of four other rock outcrops can be seen in *Figure 3*. These outcrops, called *roches moutonees*, were formed through glacial erosion and exhibit two contrasting roughness characteristics. The stoss side is formed through the mechanism of glacial abrasion [4] where the glacier flows up onto the outcrop and is characterized by a very smooth, polished surface at small scales, and a gently undulating surface at large scales. The leeward side is formed through the mechanism of glacial quarrying [5] where the glacier flows off of the outcrop and is characterized by a stepped appearance, where the

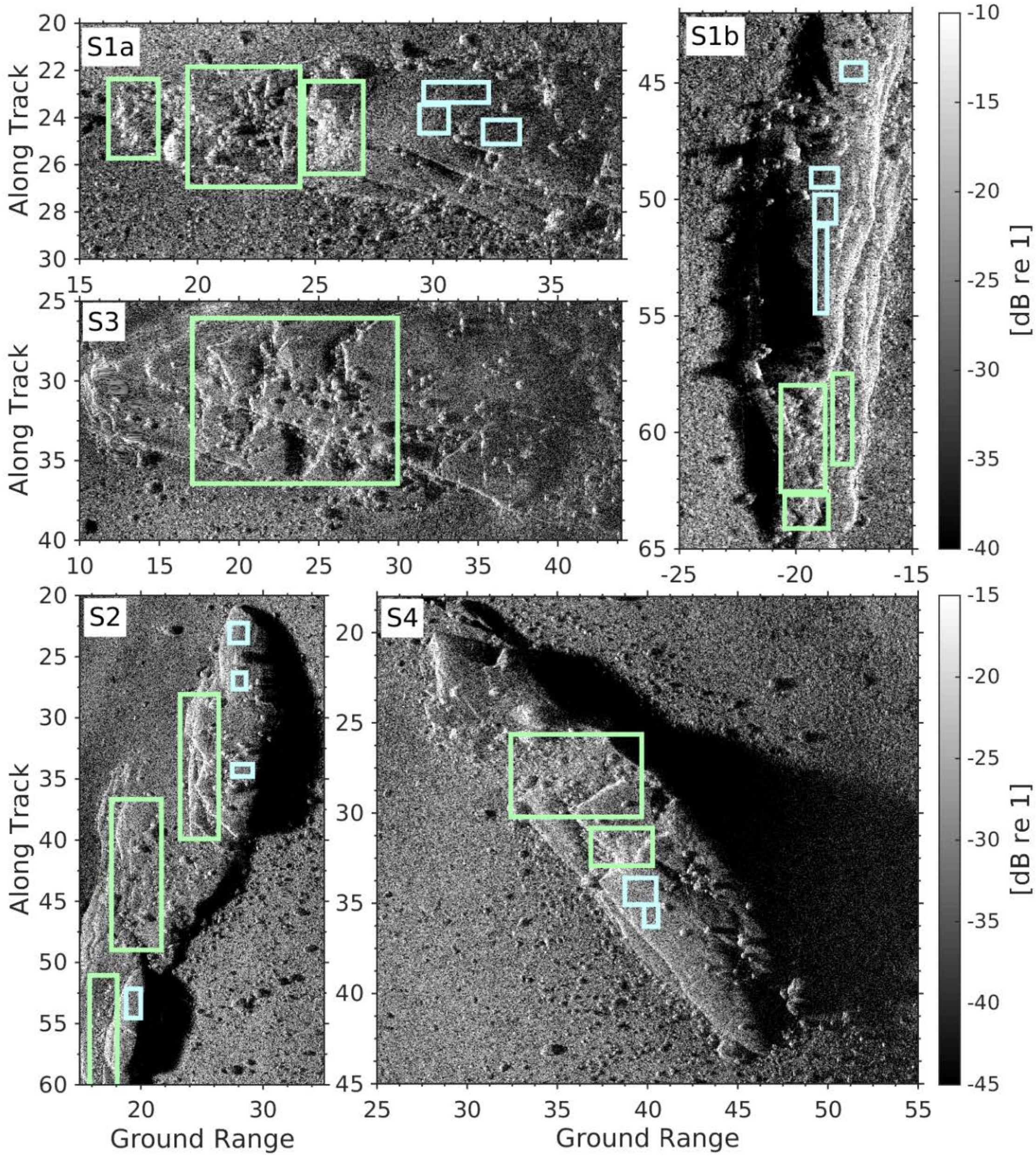

Figure 3 SAS images of roches moutonees. Image value corresponds to the unavreaged scattering cross section in dB, green boxes denote pixels used to estimate the scattering cross section of plucked areas, and blue boxes denote pixels used for abraded areas.

step sizes and orientations result from the internal joint organization of the bedrock, at scales of O(1m) and small-scale isotropic roughness resulting from fracturing at small scales (O < 0.1m). Boxes denote areas from which scattering strength was estimated, with blue boxes denoting areas of glacial abrasion and green boxes denoting areas of glacial plucking in *Figure 3*.

From the Larvik, Norway, trial, estimates of scattering strength from abraded surfaces range between -33 and -26 dB, and scattering strength from quarried surfaces range

between -30 and -20 dB. Scattering strength results are presented below, and compared to model curves. The measured scattering cross section from the plucked surfaces exhibited variability on the order of 5 dB. The abraded part of these outcrops has very low small-scale roughness, and it is likely that the scattering cross section measured on these sections can be predicted by first-order scattering models, such as the small-slope approximation (SSA). The plucked component of these outcrops has very large rms roughness compared to the wavelength, and it is likely that first-order scattering models cannot predict the scattering cross section.

The models discussed above require roughness parameter inputs for direct comparison to experimental measurements. The field experiment that was carried out in May, 2013, near the 2011 Larvik, Norway, experimental site as part of this project, was performed to provide such input parameters. Both small-scale roughness and other features affecting acoustic scattering from rock, such as facet size were obtained. Analysis continued on this data set in FY2015 and sample results will be presented below.

Scattering strength near the specular direction is difficult to estimate and simple methods, such as inverting the sonar equation, cannot be used in this case. This problem has been studied for the case of normal-incidence echosounders [6], but similar issues limit the applicability of the sonar equation for certain SAS geometries. A parametric method to estimate near-specular scattering strength from SAS data was developed in the course of the PI's graduate work [7], and was developed further in FY2015. The details of this technique are presented in [8].

We are also continuing discussion and coordination with researchers at NRL on their related project, "Modeling of High-Frequency Broadband False Target Phenomena" (project PIs are Roger Gauss, Dave Calvo, and Joe Fialkowski) as well as continuing the joint research project "Characterization and Modeling of Synthetic Aperture Sonar Data," with FFI (POC - Roy Hansen). The collaboration with NRL-DC resulted in two conference publications that will be presented at the OCEAN'15 conference in October 2015 [9] [10].

RESULTS

Roughness results from the May 2013 experiment are presented in *Figure 4* and *Figure 5* of abraded and plucked surfaces respectively. The root-mean-square (RMS) roughness, h, of the abraded surface is 2.09 mm, and 45 mm for the plucked surface. These quantities correspond to kh values of 0.86 and 18 respectively. More information on the measurements, as well as parameters extracted from the power spectra can be found in [1].

From the Larvik, Norway, trial, scattering strength from rocks was extracted from the normalized pressure squared by selecting a region and averaging in cross-range, and then averaging over one degree increments. To measure the scattering strength from a rock surface, the mean slope was determined from high-resolution interferometric bathymetry

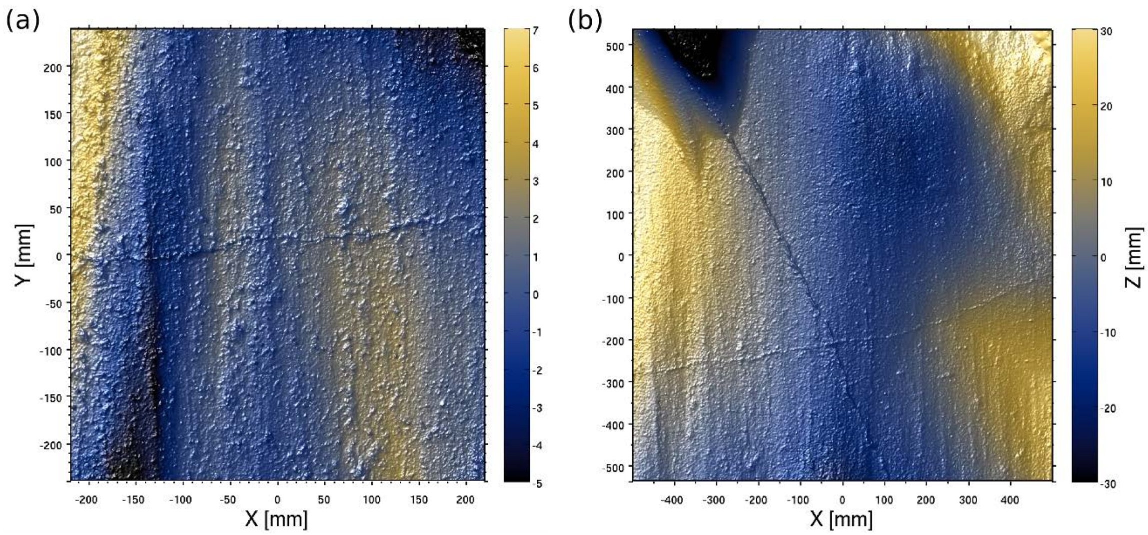

Figure 4 Interface height field results from glacially abraded surfaces obtained using stereo photogrammetry. Color denotes height in mm. The left plot (a) has a resolution of approximately 160 mm, and the right plot (b) has a resolution of 356 mm.

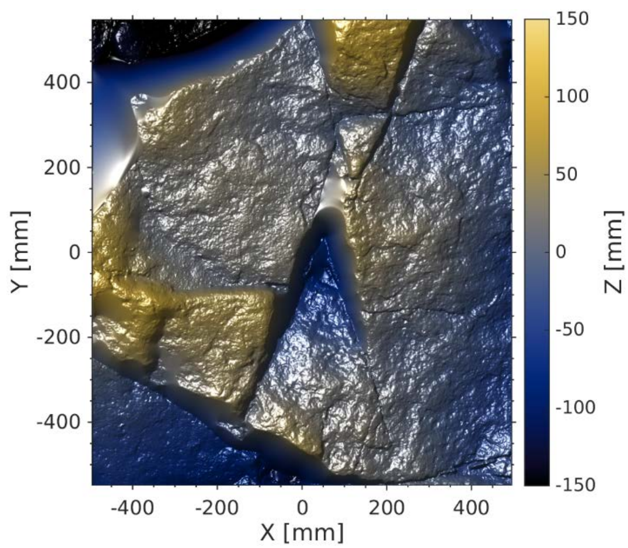

Figure 5 Interface height field results from a plucked surface using stereo photogrammetry. Color denotes height in mm, and the resolution of this height field is 356 mm.

so that the global grazing angle of the ideal mean seafloor could be mapped to the local grazing angle of the rock. Scattering strength results are presented in *Figure* 6 for abraded surfaces and in *Figure 7* for plucked surfaces. After system calibration, scattering strengths from the low-amplitude roughness of the abraded side of the rock outcrops was found to range between -33 and -26 dB at 20^{o} grazing angle, and agrees with predictions using the SSA with input parameters measured during the May 2013 experiment. This agreement is expected, since the rms height of abraded surfaces times the acoustic wavenumber is less than unity. Scattering strengths from the high-amplitude roughness of the plucked side

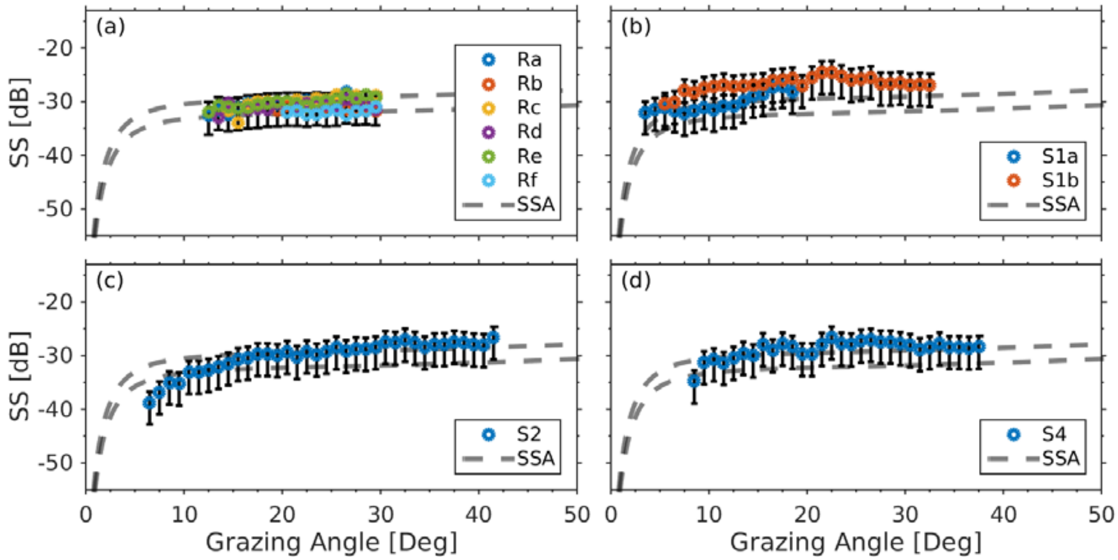

Figure 6. Scattering strength results from glacially abraded areas of rock outcrops. Comparisons are made to the small-slope approximation (SSA), which resulted in good agreement between models and data.

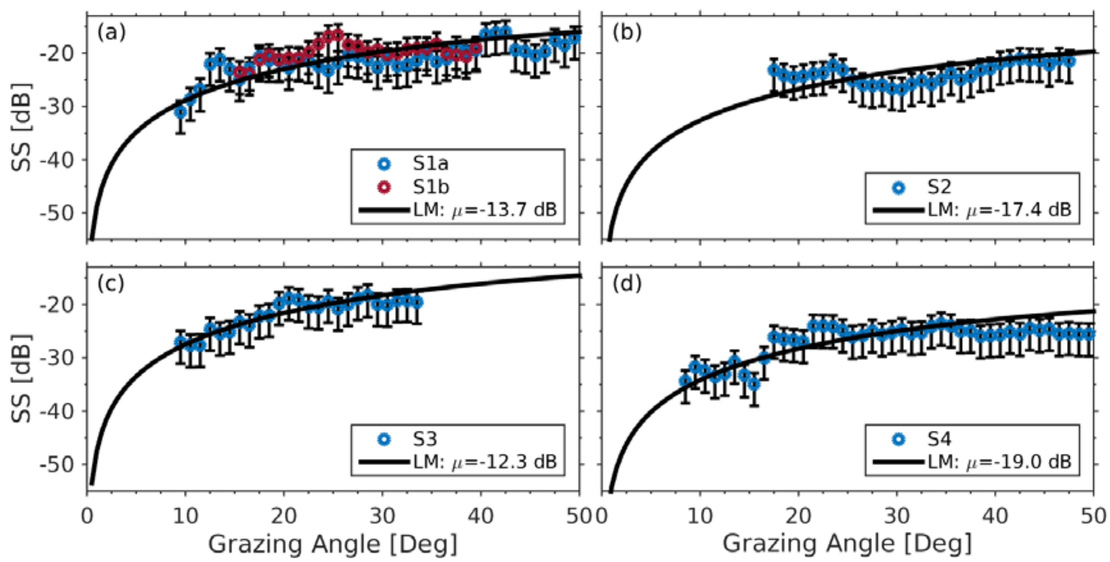

Figure 7 Scattering strength results from glacially plucked surface. The shape of the curves is agrees well with the Lambertian model, but first-order scattering models overestimate the scattering cross section by 8 dB.

ranged between -30 and -20 dB at 20° grazing angle. Predictions using small slope with measured parameters from the plucked interface resulted in an overestimate of 8 dB or more. This overestimate of scattering strength by a first-order model is unexpected, and indicates that higher-order modeling techniques may not yield acceptable predictions of scattering strength, due to the fact that higher-order terms in the cross section are typically positive-definite [11]. The composite roughness model [12] is hypothesized as a plausible

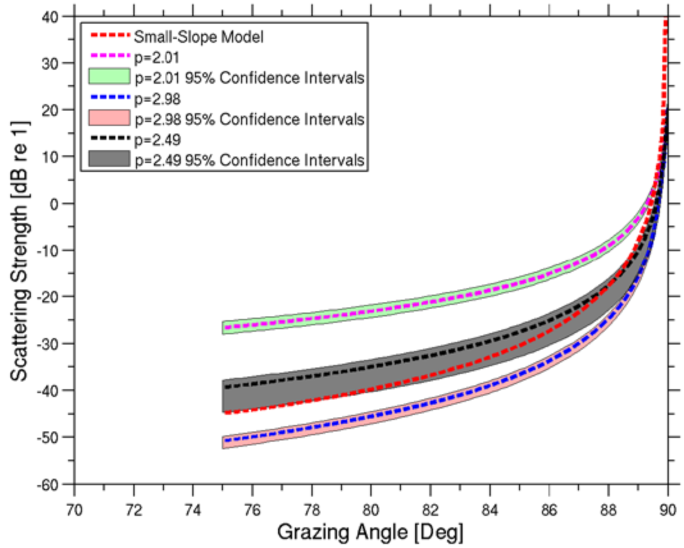

Figure 8 Scattering strength results from near-specular areas of the rock outcrops. The plots show estimates and confidence regions for three starting places in the optimization stage of the parametric estimate. These three estimates fit the data equally well, but appear to be well-separated in the scattering cross section estimate.

way forward to predict the scattering cross section from faceted surfaces when using systems that have resolution smaller than the mean facet size.

The scattering cross section near the specular direction was estimated parametrically with results presented in *Figure 8*. The estimates rely on a model whose parameters are numerically estimated, and the choice of starting location for the parameter search has an enormous effect on the final result. For three different starting locations of the parameter search, three different estimates that appear to be separated based on their confidence intervals, but in fact provide very similar fits to the SAS input data. Further analysis has shown that these estimate are only separated because their confidence intervals are assumed to be convex, which may be a poor assumption. Further investigation of the problem of near-specular scattering requires a more rigorous approach, such as Bayesian techniques [13], that can unambiguously answer questions of degeneracy and parameter correlation.

IMPACT/APPLICATIONS

The primary work completed over the course of this project consisted of developing techniques for modeling scattering from rough rock outcrop areas and comparing results with acoustic data sets collected from rocky areas. The proposed project was designed to increase our understanding of and simulation capability for acoustic scattering from rock outcrops. This study is yielding useful knowledge of rock outcrops as a mechanism responsible for shallow water false alarms and how levels of false alarm relate to physical properties and features of rock outcrops. Guidance relevant to this false alarm mechanism

is being provided to researchers at the Naval Research Laboratory and will also be provided to those developing digital simulation content as part of other programs. Other deliverables are journal articles that have been submitted, and are in preparation.

RELATED PROJECTS

PMW-120 Bottom Backscatter (BBS) Database Support Charles W. Holland (PI), Derek R. Olson (Co-PI). The prototype database being developed under PMW-120 currently has several unanswered 6.1 questions, one of which is that there is no physics-based model for scattering from oceanic crust, which is mechanism responsible for scattering from ocean ridges, and from deep-water seafloors with very thin sediment cover. In these environments, inversions from field data cannot yeild any environmental parameters. Work for the PMW-120 project will involve development of empirical models for scattering from oceanic crust. The effort will complement the glacially-eroded environements and physics-based scattering models studied in this grant.

REFERENCES

[1] D. Olson, A. Lyons and T. Sæbø, "Measurements of high-frequency acoustic scattering from glacially-eroded rock outcrops (in review)," *J. Acoust. Soc. Am.*, 2015.

[2] E. Neumann, "Compositional relations among pyroxenes, amphiboles, and other mafic phases in the Oslo region plutonic rocks," *Lithos*, vol. 9, pp. 85-109, 1976.

[3] G. Mavko, T. Mukerji and J. Dvorkin, The Rock Physics Handbook: Tools for Seismic Analysis in Porous Media, Cambridge, UK: Cambridge University Press, 2003.

[4] R. Alley, K. Cuffey, E. Evenson, J. Strasser, D. Lawson and G. Larson, "How glaciers entrain and transport basal sediment: Physical constraints," *Quat. Sci. Rev.*, vol. 16, pp. 1017-1038, 1997.

[5] B. Hallet, "Glacial quarrying: A simple theoretical model," *Ann. Glaciol.*, vol. 22, pp. 1-8, 1996.

[6] L. Hellequin, J. M. Boucher and X. Lurton, "Processing of high-frequency multibeam echo sounder data for seafloor characterization," *IEEE Journal of Oceanic Engineering*, vol. 28, no. 1, pp. 78-89, 2003.

[7] D. R. Olson, High-frequency acoustic scattering from rough elastic surfaces, The Pennsylvania State University: Dissertation in Acoustics, 2014.

[8] D. Olson, D. Brown, H. C.W. and C. Brownstead, "Where the sonar equation fears to tread," in *Proceedings of the Institute of Acoustics Conference on Seabed and Sediment Acoustics*, Bath, UK, 2015.

[9] R. Gauss, D. Fialkowski, R. Menis, D. Olson and A. Lyons, "Moment-based method to statistically categorize rock outcrops based on their topographical features," in *Proceedings of IEEE OCEANS'15*, Washington, D.C., 2015.

[10] D. Calvo, M. Nicholas, J. Fialkowski, R. Gauss, D. Olson and A. Lyons, "Scale-model scattering experiments using 3D printed representations of ocean bottom features," in *Proceedings of IEEE OCEANS'15*, Washington D.C., 2015.

[11] E. Thorsos and D. Jackson, "Studies of scattering theory using numerical methods," *Waves in Random Media*, vol. 1, no. 3, pp. S165-S190, 1991.

[12] D. R. Jackson, D. P. Winebrenner and A. Ishimaru, "Application of the composite roughness model to high-frequency bottom backscattering," *Journal of the Acoustical Society of America*, vol. 79, no. 5, pp. 1410-1422, 1986.

[13] J. Dettmer, S. Dosso and C. Holland, "Model selection and Bayesian inference for high-resolution seabed reflection inversion," *J. Acoust. Soc. Am.*, vol. 125, no. 2, pp. 706-716, 2009.

PUBLICATIONS

Olson, D.R., A.P. Lyons, and T.S Sæbø, Measurements of High-frequency acoustic scattering from glacially-eroded rock outcrops, J. Acoust. Soc. Am. In Review, 2015.

Olson, D. R, D.C. Brown, C.W. Holland and C.F. Brownstead, 2015, Where the sonar equation fears to tread. Proceedings of the Institute of Acoustics Conference on Seabed and Sediment Acoustics, Bath, UK. 7-9 September. P. Blondel, G. Heald, Holden, A. Holden, C. W. Holland, and P. Thorne, Eds. [published]

Lyons, A.P., D.R. Olson, R.E. Hansen, T.S. Sæbø, Estimation of seafloor height fields with side-looking sonar systems, Institute of Acoustics Conference on Seabed and Sediment Acoustics Conference, Bath, UK, 7-9 Sep. 2015.

Olson, D.R, 2015, Parallels in scattering research between architectural and underwater acoustics, 169th Meeting of the Acoustical Society of America, Pittsburgh, Pennsylvania

Gauss, R.C, J.M. Fialkowski, D.C. Calvo, R. Menis, D.R. Olson, and A.P. Lyons, 2015, Moment-based Method to Statistically Chategorize Rock Outcrops Based on their Topographical Features, Proceedings of IEEE OCEANS’15, Washington D.C., October 2015 [published]

Calvo, D.C., M. Nicholas, J.M. Fialkowski, R.C. Gauss, D.R. Olson, and A.P. Lyons, 2015, Scale-model scattering experiments using 3D printed representations of ocean bottom features, Proceedings of IEEE OCEANS’15, Washington D.C., October 2015 [published]

HONORS/AWARDS/PRIZES

Derek R. Olson received the 1st place best student paper award in Underwater Acoustics, 167th meeting of the Acoustical Society of America, Providence, RI, May 2014